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GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
NASA Lewis Research Center
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EXECUTIVE SUMMARY

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FOREWORD

The "Millimeter Wave Satellite Concepts" project under Contract NAS3-20110 was conducted by the Engineering Experiment Station (EES) at Georgia Tech. The program was administered under Georgia Tech Project A-1855 by the Systems Technology Branch of the Systems Engineering Division.

This report describes the work performed during the period June 1976 through June 1978. The program was managed by the NASA/Lewis Research Center Space Flight Systems Study Office. The NASA Program Manager was Mr. Grady Stevens.

The Georgia Tech Project Director was Dr. Neil B. Hilsen, Head of the Systems Technology Branch, with Mr. Larry D. Holland serving as Associate Project Director. The project was conducted under the general supervision of Mr. Robert P. Zimmer, Chief of the Systems Engineering Division. In addition to the project director and associate project director, the project team was comprised of the key personnel from the EES listed below along with their principal area of contribution.

R. W. Wallace	Communication Systems/Applications
D. L. Kelly	Annual Cost Formulation
R. E. Thomas	Systems Integration/Switching Technology
J. J. Gallagher	Millimeter/Optical Systems
F. E. Vogler	Communications Systems/Systems Analysis

SUMMARY

This research program addressed the identification of technologies necessary for development of millimeter spectrum communication satellites from a system point of view. The objectives of the program were (1) development of methodology based on the technical requirements of potential services and appropriate technologies for future NASA millimeter research and development programs, and (2) testing of this methodology with selected user applications and services. The scope of the program included the entire communications network, both ground and space subsystems. The report includes (1) cost, weight, and performance models for the subsystems, (2) conceptual design for point-to-point and broadcast communications satellites, (3) analytic relationships between subsystem parameters and an overall link performance, (4) baseline conceptual systems, (5) sensitivity studies, (6) model adjustment analyses, (7) identification of critical technologies and their risks, (8) brief R&D program scenarios for the technologies judged to be moderate or extensive risks. Subsystem models are applicable over a frequency range from about 18 GHz to 80 GHz, but the primary emphasis in the study has been for 40 and 50 GHz. Communication system costs are expressed both as total capital cost and as annual cost per channel to the user.

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SECTION 1

INTRODUCTION

Satellites have been used over the past decade for a variety of purposes ranging from scientific experiments such as measurement of the atmospheric characteristics to applications which provide improved services to society such as weather prediction, crop forecasting, and communications. The application satellites which have probably been of greatest commercial value have been the communication satellites which provide instantaneous international video communications, and have spawned a sizeable industry in so doing. Previous NASA studies [1, 2] have indicated that there will be a significant increase in both the applications and volume of satellite communications in the 1980 - 2000 time frame. Associated with an increase in demand is the potential problem of spectral crowding; obviously, some form of achieving higher capacity is necessary. One means of obtaining spectrum relief is to expand the communications services upward to the millimeter wave region of the spectrum. The larger bandwidths available at these frequencies will provide capabilities for higher data rates, and the possibility of extremely narrow beams can lead to very high reuse of the frequency assignments.

Traditionally, United States industry has enjoyed a unique capability which has led to marketing of U.S. satellite technology abroad. Introduction of proven U.S. millimeter technology could have a part in maintaining this industrial position. Hence, there exists a need to investigate the technology associated with use of the millimeter wave region of the spectrum for satellite communications. The next logical step in the development of this technology is identification of cost effective R&D paths which take into account both performance and weight constraints consistent with a practical communications satellite system.

1.1 Objectives and Scope

The primary objectives of this program were to identify the technologies necessary to satisfy communication services in the millimeter wave region and to assess the relative risks of these technologies. Specifically, these were to (1) develop a methodology based on the technical requirements of potential services that might be assigned to millimeter wave bands for identifying viable and appropriate technologies for future NASA millimeter research and development program, and (2) test this methodology with selected user application and services.

These program objectives are a subset of, and totally consistent with, an overall NASA objective of developing system concepts and plans leading to applications of bands allocated to millimeter communications satellites, and identifying necessary technologies for making the millimeter bands technically and economically competitive.

The scope of this program includes the entire communications network; i.e., ground station and satellite support as well as communication subsystems. Subsystem models which are frequency dependent are presented for frequencies ranging from about 18 GHz to 80 GHz, but the primary emphasis in the conceptual application is at 40 and 50 GHz, with supplemental results presented for 18 and 30 GHz. The final product includes (1) cost, weight, and performance models for the subsystems, (2) conceptual designs for point-to-point and broadcast communications satellite, (3) an optimization methodology for design tradeoff studies, (4) identification of critical technologies and their estimated risks, and (5) brief R&D program scenarios for those technologies judged to be of moderate and extensive risk.

1.2 Approach

The program objectives were met by an approach which employs an appropriate level of detail in the subsystem models utilized and in the numerical optimization procedure used for tradeoff analyses. The subsystem model library selection was based on the applicable subsystem models available from SAMSO [3] and Hughes [4] . Models for the remaining subsystems were developed from published specifications and from contact with personnel in the space communications industry. The overall communications link equation (received carrier-to-noise ratio) was written in terms of the independent performance parameters in the subsystem models. The total satellite system weight was expressed in terms of the same independent variables. Lower and upper bounds on the performance variables of all subsystem models were established, and a computerized random-search optimization procedure was developed for selection of the minimal cost (annual cost per channel to the user) system.

The optimization procedure was used to establish the baseline design for point-to-point and broadcast applications. Sensitivity analyses were performed for each of the baseline systems, and model uncertainty impacts were evaluated by re-optimizing the system for given percentage increases in the cost and/or weight model of interest. The resulting impact was then expressed as a likely dollar

uncertainty, and was used as a basis to rank the relative risks of the technologies required for the development and application of millimeter wave communication satellite systems.

SECTION 2

ANALYSIS METHODOLOGY

The analysis methodology incorporates a level of detail consistent with the overall objectives of the study. The subsystem models and the communication link optimization procedure are used in identifying viable and appropriate technologies for future NASA millimeter research and development programs. The sequence of development and application of the methodology was as follows:

1) development of models for cost and weight of spacecraft subsystems;
2) development of the overall link carrier-to-noise ratio equation;
3) development of cost optimization methodology;
4) generation of conceptual designs for point-to-point and broadcast communication satellites;
5) optimization of each of the two conceptual system designs;
6) performance of sensitivity and model adjustment analyses; and
7) selection of critical technologies and performance of risk assessment.

2.1 Subsystem Models

The ground and space subsystems and their categorizations are indicated in Figure 2.1. This shows the specific subsystems that were modeled to represent the overall communication link. Parametric cost and weight models were formulated for each of the subsystems included in the satellite/ground configurations. In most cases there is one major driving parameter affecting the cost while several minor parameters are used to specify features of the configuration. The weight models normally have the same independent variables as the corresponding cost models. In cases where total satellite weight is the independent variable for a subsystem weight model, an iterative technique is required for computations. A summary of the cost and weight model driving parameters is given in Table 2.1.

The individual subsystem models are applicable over a specified range of the performance parameters, and the models are continuous (though not necessarily differentiable) over the allowable range of the performance parameters.

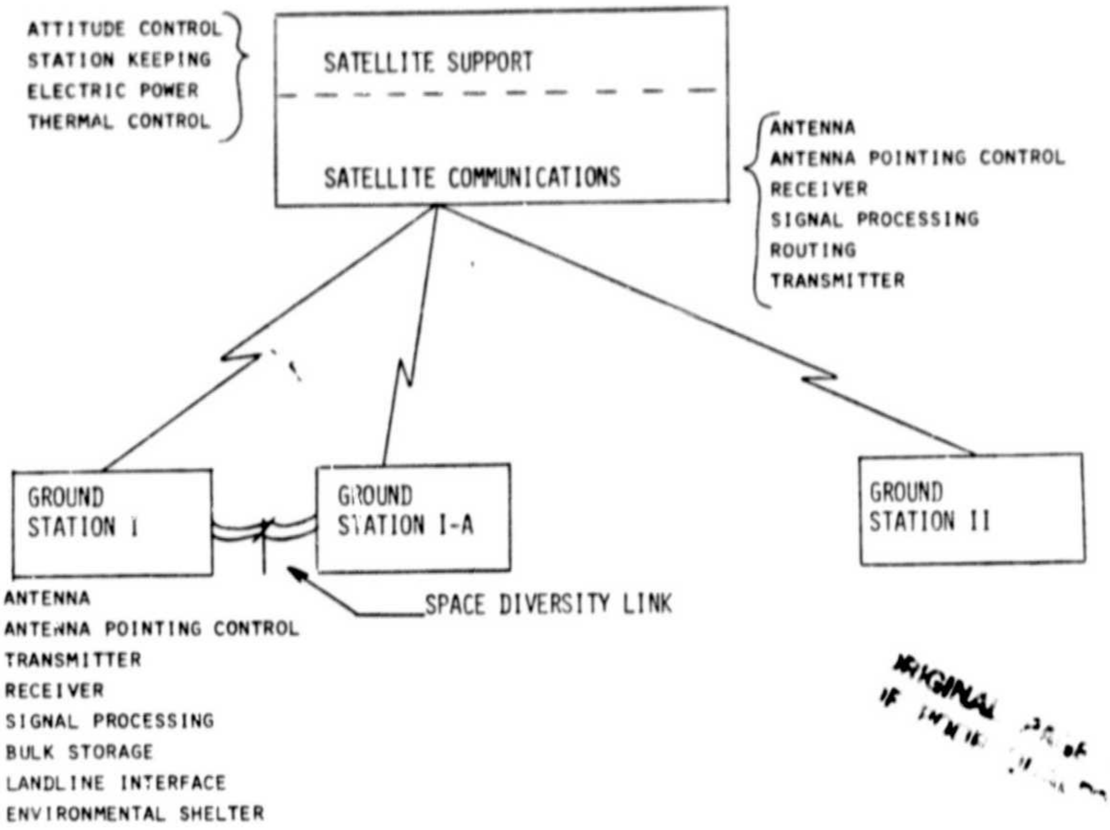

FIGURE 2.1 GROUND AND SATELLITE SUBSYSTEM CATEGORIES

TABLE 2.1 SUBSYSTEM COST AND WEIGHT MODEL DRIVING PARAMETERS

Subsystem Cost Models		Subsystem Weight Models	
Subsystem	Driving Parameters	Subsystem	Driving Parameters
Ground Antenna	Dish Diameter Transmitter Frequency	Satellite Antenna	Antenna Diameter Operating Frequency Number of Feeds
Radome	Radome Diameter		
Ground Pointing and Control	Pointing Error Dish Diameter	Satellite Transmitter	Transmitter Power Operating Frequency
Ground Transmitter	Transmitter Power Transmitter Frequency	Satellite Signal Processing	Number of Channels Number of Subchannels per Channel
Ground Receiver	Receiver Noise Figure Receiver Frequency		
Ground Signal Processing	Baseband Channel Bandwidth	Attitude Control System	Attitude Control Error Satellite Weight
Bulk Data Storage	Data Rate Storage Volume	Station Keeping System	Station Keeping Accuracy Satellite Weight
Landline Interface	Data Rate Number of Television Headins Number of Voice Multiplexors	Structure and Thermal Control	Satellite Weight
Diversity Link	Diversity Range	Satellite Power Supply	Prime Power Required
Satellite Antenna	Antenna Diameter Operating Frequency Number of Feeds		
Satellite Transmitter	Transmitter Power Operating Frequency		
Satellite Receiver	Noise Figure Operating Frequency		
Satellite Signal Processing	Number of Channels Number of Subchannels per Channel		
Attitude Control System	Attitude Control System Weight		
Station Keeping System	Station Keeping System Weight		
Structure and Thermal Control	Structure and Thermal Control Weight		
Satellite Power Supply	Prime Power Required		

2.2. Link Optimization

The inter-relationship between the cost models, weight models, link equation, and weight budget during system optimization is demonstrated in Figure 2.2.

The methodology for optimization of the communication link selects all subsystem performance parameters in such a way that the overall link carrier-to-noise ratio requirement, and the satellite weight constraint are satisfied, and the total system cost is minimized.

A random search algorithm which uses a computerized random number generator to select trial points over the parameter intervals was developed and used for most of the optimizations performed during the program. The algorithm reduces the parameter interval in successive optimizations until the density of random points selected is quite high in the final optimization step. This methodology has proven to be effective and efficient. However, for applications in which the optimal solution lies on the weight boundary, the random search algorithm requires a significant increase in computer time. As a result, an interactive man-in-the-loop gradient search algorithm was also developed as an option to the random search procedure. Use of this option (from a remote computer terminal) has significantly decreased the computer time for establishing the cost-optimal conceptual design of the satellite broadcast analysis. A block diagram of the Satellite Cost Optimization Routine (SCOR) is shown in Figure 2.3.

2.3 Sensitivity and Model Adjustment Analyses

Application of the cost minimization routine, SCOR, to a satellite communication system conceptual design yields optimal values for each of the subsystem performance parameters. A question of how critical a specific parameter might be is usually resolved by performing a sensitivity analysis with respect to the optimal parameters. Such an analysis indicates, for each of the parameters, the change in total system cost as a function of a small change in a parameter value. In applications of SCOR, the sensitivities of the total system cost, satellite weight, and link carrier-to-noise ratio are calculated and tabulated for each computer analysis. The calculations are open-loop in that incremental changes are calculated without reoptimization, but presentation of sensitivities of cost, weight, and link figure-of-merit allow direct determination of the effects upon performance.

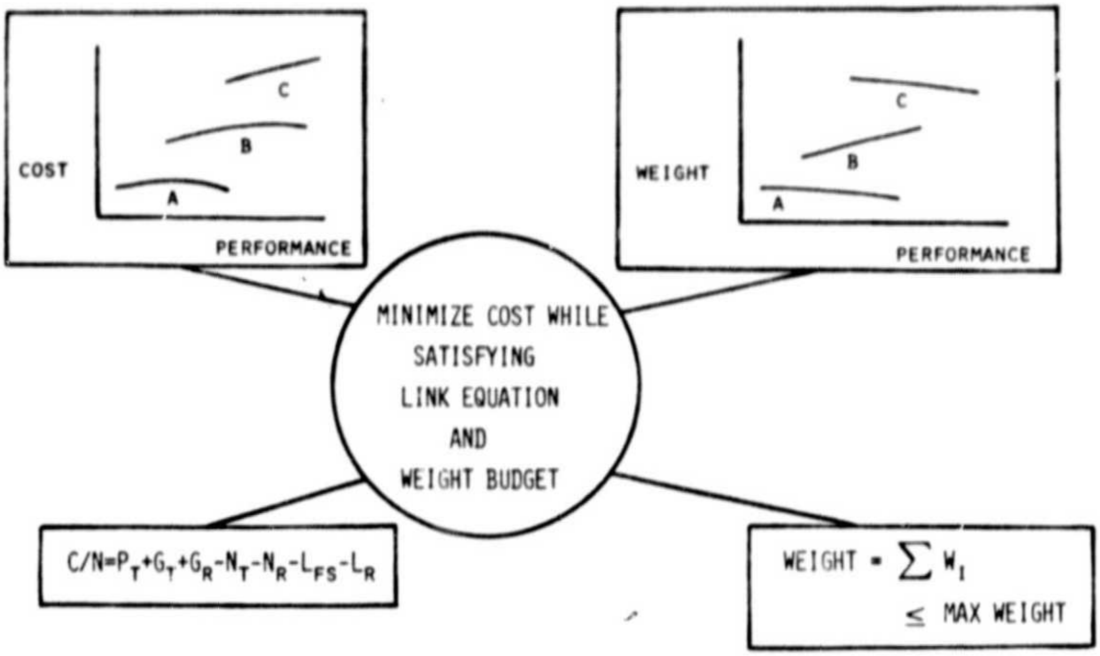

FIGURE 2.2 ANALYSIS TECHNIQUE

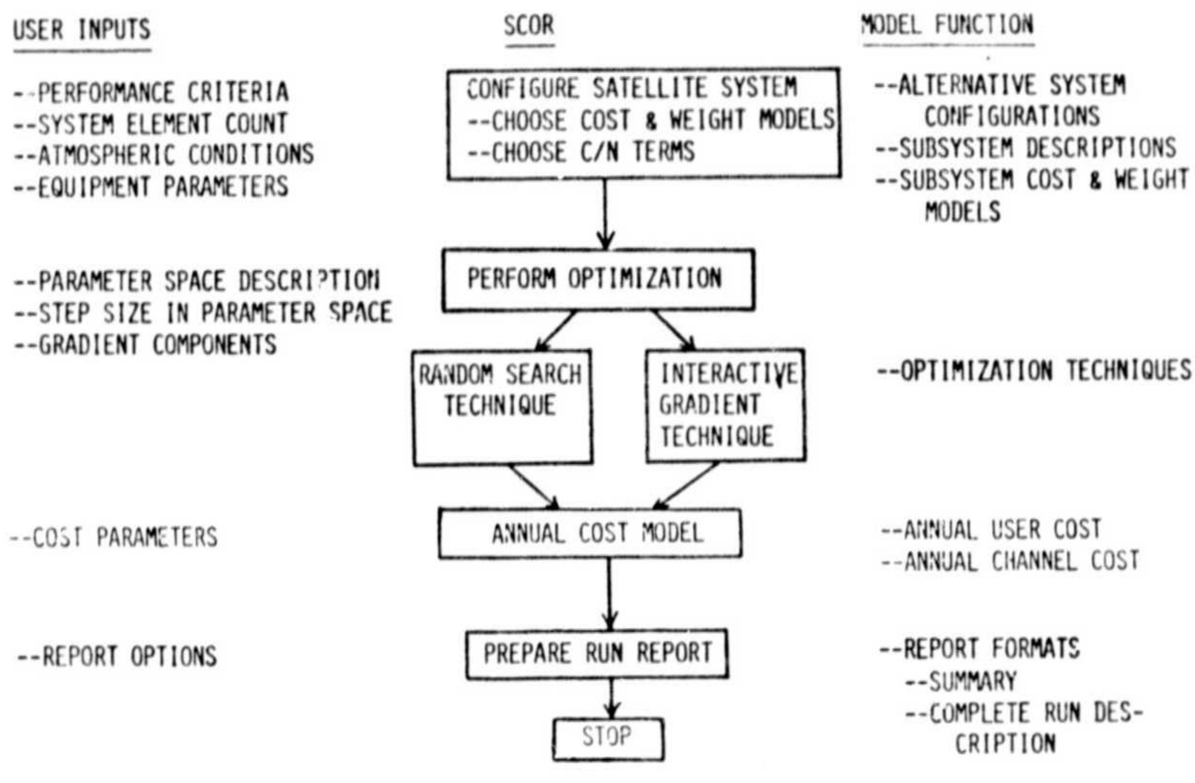

FIGURE 2.3 BLOCK DIAGRAM OF THE SATELLITE COST OPTIMIZATION ROUTINE (SCOR)

The effect of significant variations in the cost and weight models was evaluated by a model adjustment analysis. In this analysis, the parameter values of each cost or weight model was doubled while holding constant all other models, and repeating the total optimization procedure. Results of the reoptimizations which are of interest include the impact on total system cost and the manner in which subsystem performance parameters are changed as a result of the model adjustment. This analysis was then used as a first step in establishing which subsystems and related technologies are critical; that is, which technologies are responsible for the greatest impact in the overall system cost, or equivalently, in the feasibility of the conceptual design.

2.4 Critical Technology Selection and R&D Risk Assessment

The model adjustment analysis, when combined with estimates of the likelihood of occurrence of model changes, provides a measure of criticality of the subsystem and its associated technologies. The final identification of technologies which are critical, then requires three additional steps: (1) identification of uncertainty levels with each subsystem; (2) estimation and ranking of subsystem uncertainty impacts; and (3) relating subsystem impact to the specific technologies.

Initial qualitative estimates of the subsystem model uncertainties are assigned quantized likelihoods (10%, 30%, 50%, 70%, or 90%). The likelihood number may be viewed as an approximate probability that the model adjustment utilized in the model adjustment analyses will actually occur. The product of this likelihood number and the increase in total system cost resulting from that subsystem model adjustment is a measure of the resulting system impact. The subsystems are then ranked according to the estimated system impact of uncertainty. The technologies associated with the subsystems having the higher estimated system impact will then be isolated for risk assessment.

Once the set of technologies which are critical to the millimeter space communication system have been identified, it is desirable to estimate the risks associated with advancement of each technology. The primary measure of risk is the time required for conducting an R&D program to adequately reduce both the uncertainty and the base value of the cost and weight characteristics of the technology.

The estimated risk (R&D time requirement) is estimated for each of the technologies associated with the subsystems with high ranking estimated system cost impact. The risk of these technologies is then categorized as being short-term (2-4 years), long-term (5-10 years), or unknown term (requiring an invention). The estimated risk is based on the judgement of professionals knowledgable of the state-of-the-art for the specific technology.

SECTION 3

COMMUNICATION SATELLITE APPLICATIONS

The purpose of developing user applications was to provide a realistic background for the development of subsystem models and to demonstrate the use of the SCOR model in evalating proposed satellite communication systems.

3.1 Application Selection

There are many potential applications of millimeter wave communications satellites in both the public and private sector. This study used two basic systems which could be adopted for a variety of specific end users. For convenience the two basic systems were designated point-to-point and broadcast. The point-to-point system provides broadband (1 GHz) communications among a relatively small number of earth terminals, whereas the broadcast system provides narrowband (50 MHz) communications among a relatively large number of earth terminals.

Both of the applications were based on a number of common assumptions. Due to the anticipated pointing accuracy requirements, a body-stabilized satellite was assumed. To maintain reasonable earth station tracking requirements, the satellites were assumed to be in a geo-stationary orbit (about 35,000 km) positioned over the middle of the continental United States. An available RF bandwidth of one GHz was assumed for both applications on uplink and downlink. The uplink frequency was considered to be in the 50 GHz band while the downlink was considered to be 40 GHz.

3.2 Application I: Point-to-Point

A baseline conceptual system was developed for the point-to-point application which uses six ground stations each with single station diversity for both receive and transmit. Figure 3.1 shows the geographical coverage area. It was assumed that no radomes are used to protect the ground antennas. For baseline analysis, all signal processing was assumed to be by frequency-division multiplex. As for all analyses performed to calculate system cost, the cost for the baseline system was minimized by the computer program SCOR under carrier-to-noise and weight constraints.

A complete set of the parameters required for input to this minimization is given in Table 3.1. Included are system constraints, system configuration pa-

FIGURE 3.1 APPLICATION I COVERAGE AREA OF POINT-TO-POINT COMMUNICATIONS BETWEEN CITIES (CIRCLED)

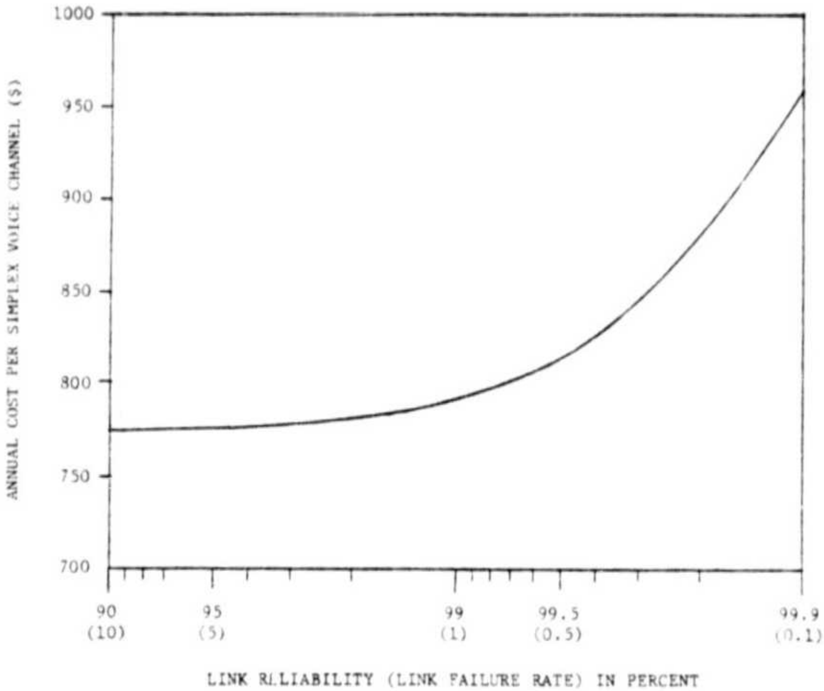

FIGURE 3.2 ANNUAL COST PER CHANNEL VERSUS LINK RELIABILITY FOR POINT-POINT SERVICE AT 40/50 GHz.

TABLE 3.1 POINT-TO-POINT APPLICATION BASELINE PARAMETERS

PARAMETERS	VALUE
Carrier/Noise Constraint Limit (DB)	15.00
Weight Constraint Limit (LBS)	5000
Downlink Frequency (GHZ)	40.50
Uplink Frequency (GHZ)	50.50
Satellite Channel Bandwidth (MHZ)	1000.
Number of Channels (Beams)	6
Number of Positions Per Beam	1
Reliability (Percent)	99.90
Rain Rate (MM/HR)	50.00
Number of TV Headins	12
Number of Voice Muxes	12
Digital Data Rate (MBS)	3.000
Bulk Data Rate (MBS)	200.0
Bulk Data Volume (MB)	1000.
Number of Ground Stations	6
Ground Transmitters Per Link	6
Ground Receivers Per Link	2
Channel Capacity	66.300
Number of Subchannels Per Channel	5
Ground Station Bandwidth (MHZ)	1000.
Diversity Link Receive Cost (K$/MI)	100.7
Diversity Link Transmit Cost (K$/MI)	40.30
Diversity Link Range (MI)	9.940
Ground Station Building Cost (K$)	100.0
Diversity Station Building Cost (K$)	50.00
Marginal Income Tax Rate	0.48
Rate of Return on Investment	0.13
Financial Planning Horizon (Years)	8
Life of Satellite (Years)	8
Life of Ground System (YEARS)	14
Tax Constant	0.015
Insurance Constant	0.012
Cost of Debt	0.085
Ratio of Debt to Total Capitalization	0.45
Fraction of Channel Sellable	0.50
Average Growth of Operating Costs	0.065
Satellite Operating Cost Constant	0.01
Ground System Operating Cost Constant	0.04
Launch Cost (K$/LB)	5.0
Launch Insurance Rate	0.1
Number of Satellites Purchased	3
Number of Launches	2
Uplink Misc. Losses (DB)	7.000
Downlink Misc. Losses (DB)	8.000
Atmosphere Temperature (K)	300.0

rameters, and various assumed constants. The results of the analysis for this three-satellite (two in orbit, one spare on ground) system include annual cost data and capital costs. The total capital cost for the optimized system is $112.7M. This translates to an annual system cost of $31.8M and a per simplex voice channel annual cost of $959 (for 50% utilization). Figure 3.2 shows that as link reliability increases from 90% to 99.9%, the annual cost per simplex voice channel increases from $775 to $959.

3.3 Application II: Broadcast

For this application, the interconnection of a large number of earth stations throughout the United States was considered. Total ground coverage is required, although not simultaneously. In concept, however, an earth station located anywhere within the U.S. should be able to communicate with an earth station at any other point in the U.S. through this satellite. Each earth station must be capable of transmitting full bandwidth television or 1.544 Mbps data as a minimum. The geographical coverage area of Application II is shown in Figure 3.3. This figure shows the number of beams required for the coverage which will vary depending upon power available, pointing capability, and simultaneous user requirements.

The objective of the broadcast application concept was to provide total U.S. coverage using adjacent spot beams with 99.5% link reliability (rain considerations only) for wideband uses such as video distribution. Preliminary power calculations indicated that very large (heavy) satellites would be required for this concept, and a compromise baseline design with limited simultaneous beam utilization and with on-board switching was developed. This design provides up to 96.5% link reliability with the assumed subsystem constraints.

Figure 3.4 gives a plot of annual cost per wideband channel as a function of link reliability. Link reliabilities higher than 96.5% were not possible under the system constraints without the use of diversity stations. Note that there is approximately a 15% increase in cost per channel as the reliability increases from 90% to 96.5%. This is a straight line plot connecting reliability points at 90%, 95%, and 96.5%; hence the break at 95%.

In order to examine the cost per terminal for various numbers of ground terminals and for various communication capabilities, channel availability was defined as the ratio of the total number of channels to the number of ground

FIGURE 3.3 MILLIMETER WAVE SATELLITE APPLICATION II COVERAGE AREA WITH CIRCLES REPRESENTING COVERAGE OF INDIVIDUAL BEAMS

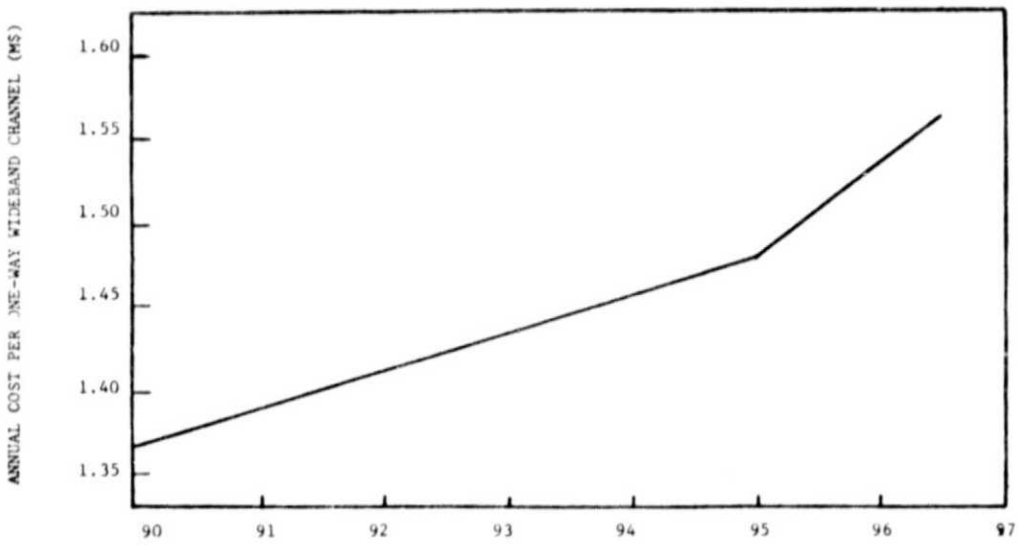

FIGURE 3.4 ANNUAL COST PER WIDEBAND CHANNEL VERSUS LINK RELIABILITY

terminals. Figure 3.5 gives annual cost per wideband terminal versus availability for 120, 360, and 1080 ground stations. Utilizations (channel availability) greater than 0.22 were not possible for 1080 ground stations due to absolute launch weight limits.

The increase in cost per terminal is approximately linear with increases in utilization for all numbers of ground stations. The cost increase is due to adding many more switching components and the resulting effect this has on launch weight for a larger satellite operational system.

For a constant utilization, the cost may be studied for various numbers of terminals. For the increase from 120 to 360 ground stations, the drop in per terminal cost is a result of the further division of satellite cost. For the increase to 1080 ground stations the decrease is less than would be expected due to substantially increased launch cost for the heavier satellite.

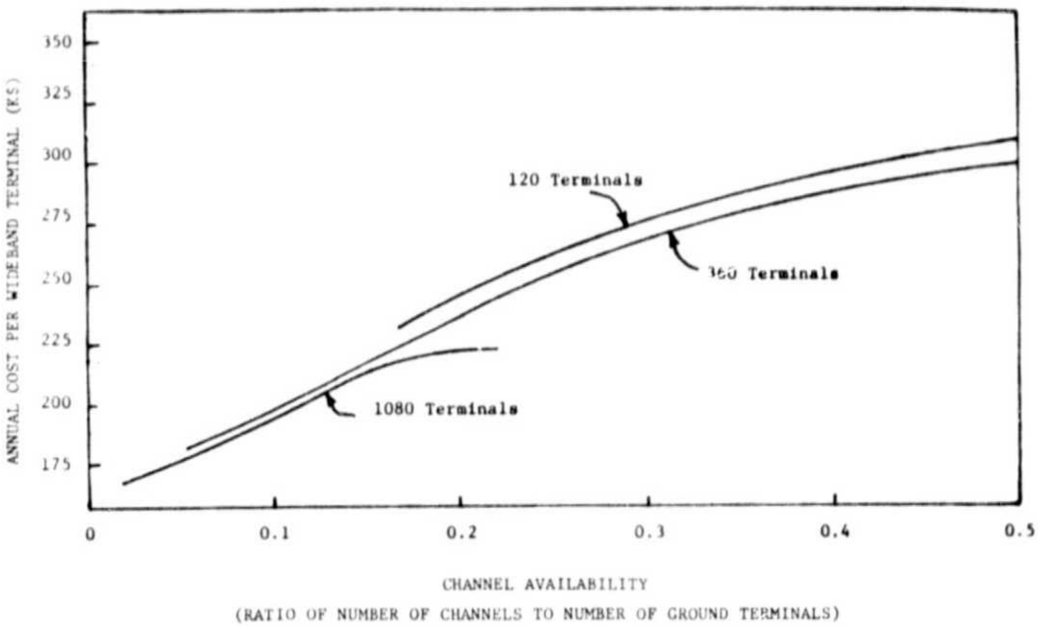

FIGURE 3.5 ANNUAL COST PER WIDEBAND TERMINAL VERSUS CHANNEL AVAILABILITY FOR 95% RELIABILITY.

SECTION 4

TECHNOLOGY RISK ASSESSMENT

Identification of technologies critical to implementation of millimeter space communication systems requires accomplishing the following four items:

1) evaluating the system impacts of model adjustments (by reoptimization for each adjustment);
2) identifying the likelihood of model adjustments for each subsystem;
3) estimating and ranking expected system impacts; and
4) relating expected system impacts to specific technologies.

These steps were applied to the point-to-point and broadcast applications. The results from the applications were then combined to produce an overall listing of critical technologies for millimeter wave space communications systems. Table 4.1 presents this list of critical technologies categorized by risk (i.e., the R&D time required for technology improvement).

Program scenarios were developed for several of these critical technologies. The objective of these programs are to provide research and development to reduce the cost and improve the performance of the technologies. Brief summaries of these scenarios follow.

Propagation

By far, the one item of greatest impact on the results of this study was the assumed propagation fade statistics. Consequently a more refined engineering analysis of 40/50 GHz communications should await basic data from satellite experiments in the 40/50 GHz region. The scale of these data should be comparable with the work performed at lower frequencies. The propagation studies are more difficult at these wavelengths not only because of the increased clear air attenuation over that existing at lower frequencies but also because of the increased attenuation resulting from rain and cloud coverage. As a result of these factors, propagation of millimeter waves has exhibited severe fluctuation effects and has been difficult to analyze. The research required for millimeter wave propagation could be done in conjunction with other experimental work requiring geosynchronous satellites and allowing the additional payload of a group of millimeter wave beacons.

TABLE 4.1 TECHNOLOGY RISK ASSESSMENT

Subsystem	Risk Category*
Structure & Thermal Control	A
Satellite Signal Processing	B
Landline Interface	A
Diversity Landline	A
Bulk Data Storage	C
Ground Pointing and Control	A
Station Keeping	A
Ground Transmitter	A
Satellite Antenna	A
Satellite Transmitter	B
Ground Receiver	A
Satellite Receiver	A

*Risk Category Definition:

A = 2 - 4 years
B = 5 -10 years
C = Invention Required

High Data Rate Diversity Line

In choosing the means of transmitting between two spatial diversity sites, several techniques were considered. From the viewpoint of size and operation during inclement weather, the buried millimeter wave link and fiber optic system have the greatest potential. These two schemes also provide the greatest capability for high data rate transmittion. Substantial research and development efforts are already under way in both these areas and it is doubtful that additional effort would be called for. At this time it would appear that the buried waveguide and optical fiber technologies will be competitive. However, because of its large contribution to the overall cost of the satellite communication system (Application I), the diversity link costs must be substantially reduced and/or the link operated with high traffic loads.

Bulk Data Storage

The attractive capability of millimeter wave communications to provide near 1 Gbit data rates is severely limited by the interface of the communication to the users. It is always necessary to provide buffer storage which operates at these high data rates. Currently, solutions require high parallelism in digital equipment and correspondingly large costs. Several technologies have been suggested which may eventually accomodate these applications, but none is sufficiently developed to allow estimates of availability.

Since there is strong motive for the development of high data rate storage in the computer industry, it is likely that additional research sources will not speed the process. Rather, research should be limited to determining new advances in the area and judging their impact on the attractiveness of millimeter digital communications.

Space Switching Equipment

Switches for application in millimeter wave communications applications are currently available but are considered too bulky for the large capacity systems of interest. The development program for these components would be to provide reliable ferrite switches while taking advantage of the inherent small size of millimeter devices. Special attention should be given to the use of these switches in matrix arrangements with configurations adapted to satellite communication requirements.

This problem is primarily one of engineering design; most of the work is that of prototype construction and testing. Flight tests are required primarily for reliability and life-time analysis. After the switching capacity requirements are specified it is estimated that development can be completed in 2 years.

Receiver and Transmitter

Because of the high loss propagation characteristics of millimeter waves, improvements in system performance will depend heavily on the availability of high performance receivers and transmitters. In particular, the weight of the spacecraft transmitter is especially critical. With our assumed models, it appears these devices would account for a substantial portion of spacecraft weight. In some configurations the required satellite weight exceeded launch capabilities.

By our estimates a 2 lb. reduction in spacecraft weight can be realized for every 1 lb. reduction of transmitter weight. The 2:1 leverage occurs because of the reduced requirements for structure, attitude control and station keeping. Our analyses indicate only a modest RF power requirement per device for Application I. However, the total RF power required is substantial requiring a significant weight penalty in the thermal control system. In Application II the required RF power and thermal control capacity per transmitter were substantial and severely restricted satellite payload.

Therefore, emphasis in the technology effort on spacecraft transmitters should be on lightweight devices, efficient operation, and modest to high power outputs. Both the spacecraft and ground terminal receivers should have a relatively low noise performance. It appears appropriate to consider cryogenically cooled types for the ground terminals while uncooled types may suffice for the spacecraft.

Satellite Antennas

Two areas of satellite antenna development are of interest in millimeter wave communication applications. One is to improve the tolerance of dish or lens fabrication to reduce error tolerances. At millimeter wavelengths this allows significantly improved antenna gain. The second is further development of multibeam antenna techniques, an important adjunct to the switch capacity of a communication satellite. Each of these areas requires further engineering studies to improve construction techniques and to decide among alternative designs. Work is currently underway for both of these design efforts. Consequently, it is

expected that 2 years is sufficient for adequate development after system requirements are defined.

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

Identification of technologies for millimeter satellite communication systems, and assessment of the relative risks of these technologies, were accomplished through subsystem modeling and link optimization for both point-to-point and broadcast applications. The methodology developed for identifying viable and appropriate technologies for future NASA millimeter research and development programs is based upon the technical requirements of potential space communication services. Applicability of the methodology was verified through its use with two conceptual communications systems. The subsystem cost and weight models were developed to the appropriate level of detail for this study. Application of the methodology to the detailed design of a satellite system would require further model refinement.

Propagation statistics for the ground station locations will significantly influence the design and, therefore, the cost of millimeter space communication systems. One of the primary results of the study relates the link reliability (percent of the time the link is operational) to assumed weather statistics and, in the case of the point-to-point service, an assumed ground station diversity.

For the point-to-point service (Application I) redundant transmitting/receiving stations were located approximately ten miles from the normal ground station. Link reliabilities of 90.0% to 99.9% were available with this configuration at varying system costs. As shown in Figure 3.2, typical annual costs to the user for a voice grade channel on a 40/50 GHz satellite system is approximately $150. This compares with current costs of about $3,500 to $6,500 annually for a simplex voice channel. The bulk of this difference is an economy-of-scale effect arising from the use of very high capacity satellites.

The broadcast concept (Application II) initially considered provided continuous continental United States coverage through a large number of adjacent spot beams. However, preliminary power calculations indicated that excessive satellite weight would be required for this mode of operation. A compromise baseline design incorporating limited simultaneous beam utilization with on-board switching was then selected for analysis. The weight of the switches became a limiting criterion in overall performance. The resulting "broadcast" link was estimated to be able to maintain its design value carrier-to-noise ratio (12dB) 95% of the time

for the assumed rain attenuation statistics. Such a communication satellite system would not be commercially marketable in the sense of current communication satellites (e.g., video entertainment); however, there may well exist suitable applications such as high volume data transfer where the time of day for the data transfer is not critical.

For the broadcast application, the primary consideration was the launch capability; the ground station diversity was not considered to be a viable option. The system cost model indicated a need for a high power (and heavy) satellite with small inexpensive ground terminals to realize lowest costs. However, the minimum annual cost appears to be about $200,000 per terminal or $1.5M per wideband channel. This compares with a current cost of $1M per wideband channel. The link reliability for the broadcast case was limited to near 95% for a 6500 pound satellite. The reduced reliability for this service is a result of the need for a large number of switches, significant power requirements, and launch constraints. In addition to the broadcast mode user costs being somewhat higher than current commercial costs, it is more important to note that these projected costs correspond to a 95% link reliability as compared to the current commercial case at the lower frequency with reliability in excess of 99%.

Technology risks were defined for those technologies deemed most critical to the cost of an overall millimeter communication system. The critical technologies include all receivers and transmitters, bulk data storage, diversity landline, satellite switching and satellite antennas.

It is recommended that additional experiments in and analyses of atmospheric propagation characteristics and specific technology research intended to reduce the costs of subsystems be conducted. It is also recommended that the methodology and models developed here be extended to other applications such as navigation satellites where maximum advantage can be taken of existing methodology and models.

Further investigation of satellite broadcast applications at millimeter frequencies is required. Such investigations should be directed toward increasing the link reliability by the use of multiple satellites and massive satellites to provide sufficient RF power to assure communications through moderate rainstorms. The commercial marketability of applicable services should also be investigated.

Other recommendations relative to implementation of advanced communication satellites would include additional research in on-board signal processing, direct modulation for receive/transmit at 50/40 GHz, data regeneration for use

with digital transmission, investigation of additional methods of bulk data storage and methods for efficient use of space communication links with variable data rate users.

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